CF6 HIGH PRESSURE COMPRESSOR AND TURBINE CLEARANCE EVALUATIONS

M.A. Radomski and L.D. Cline
General Electric Company

SUMMARY

In the CF6 Jet Engine Diagnostics Program the causes of performance degradation were determined for each component of revenue service engines. It was found that a significant contribution to performance degradation was caused by increased airfoil tip radial clearances in the high pressure (HP) compressor and turbine areas.

Since the influence of these clearances on engine performance and fuel consumption is significant, it is important to accurately establish these relationships, especially now when fuel prices are rapidly escalating. It is equally important to understand the causes of clearance deterioration so that they can be reduced or eliminated.

This paper describes the results of factory engine tests run to enhance the understanding of the high pressure compressor and turbine clearance effects on performance. It also indicates the causes of clearance deterioration and discusses potential improvements in clearance control.

INTRODUCTION

The CF6 Jet Engine Diagnostics Program showed measurable degradation of compressor and turbine airfoil tip clearances in revenue service engines.

The degradations of the compressor tip clearances were caused by spalling of abradable coatings from the stator casings and rotor spools, by blade and vane tip rubs and by field assembly procedures involving out-of-round stator casings. Degradation of clearances in the CF6 compressor was estimated to produce, on the average, a 0.4 percent increase in the specific fuel consumption at cruise. This is estimated to amount to 15 million gallons per year for the 1981 CF6 engine fleet.

The effect of compressor clearances on compressor efficiency has been studied at General Electric for many years using a low speed research compressor. The data obtained from this research vehicle have been applied to the compressors of the CF6 engine family. Attempts have been made to verify these data by power calibrations of the CF6 production engines, but they have not been entirely successful because, in these tests, compressor efficiency was affected by several factors, and the effects of the airfoil tip clearances alone on efficiency could not be isolated with accuracy. There was, therefore, a need to conduct instrumented CF6 factory engine tests to accurately verify the influence of compressor clearances on engine performance.

The tests were conducted as part of the CF6 Jet Engine Diagnostics Program using an instrumented core engine.

The high pressure turbine tip clearance degradation was caused by blade tip rubs on the stator casing. The major cause of rubs was out-of-roundness. The principal causes of HP turbine out-of-roundness are the thermal gradients and transient responses of adjacent structures, such as the compressor rear frame, turbine mid-frame, and the low pressure turbine case. The increase in HP turbine clearances was estimated to contribute, on the average, a 0.6 percent increase in cruise specific fuel consumption. This equates to approximately 22 million gallons per year for the 1981 CF6 engine fleet.

Accurate measurements of HP turbine clearances and out-of-roundness have been difficult to achieve until now. Rub pins and High Energy X-Ray (HEX) tests have yielded reasonable approximations to date. The current performance sensitivity factors are based on turbine efficiency sensitivities established during air turbine testing and SFC effects determined from the engine cycle deck. Direct, on-engine analysis of the sensitivity factors related to turbine clearance were required to determine the turbine's contribution to overall engine performance deterioration. A test program was conducted as part of the CF6 Jet Engine Diagnostics Program to evaluate the effects of stator out-of-roundness and stage 1 blade tip clearance upon performance.

This paper outlines the scope of the HP compressor and HP turbine clearance evaluation programs, describes the unique instrumentation and the test procedures used, discusses the data reduction and presents some preliminary results.

HIGH PRESSURE COMPRESSOR CLEARANCE EVALUATION

Program Scope

The program was designed to determine the influence of compressor clearances on engine performance and also to evaluate potential improvements in clearance control. The approach used was to run instrumented core engine tests in which airfoil tip clearances were varied by varying quantities of rotor bore cooling air. The greater the cooling air flow, at any power setting, the lower was the bulk temperature of the rotor structure and, hence, the greater were the tip clearances. The running clearances were calculated from measured temperatures of the stator and rotor structures. The calculations were verified using measured blade tip clearances in stages 10, 12 and 13. The clearance changes and the corresponding measured performance changes were then correlated.

Rotor Bore Cooling - Externally supplied shop air was used to cool the rotor and thus vary the clearances. The total cooling air flow was measured by an instrumented orifice and remotely controlled by a valve upstream of the orifice shown in Figure 1. From the orifice, the air flowed to the manifold around the slave front frame, from there through flexible hoses into the frame struts and then into the HP compressor inlet inner cavity shown in Figure 2. From this cavity, some of the air leaked out through the air/oil and air seals bounding the cavity (only the rotating seals are shown in the figure) and the remainder, the net cooling air flow, entered the rotor main cavity through the holes in the forward shaft. The cooling air exited the rotor cavity through holes in the rear shaft and from there was discharged through the compressor rear frame struts into the test facility exhaust. The net cooling air flow was calculated for each test point by subtracting the seal leakages from the total measured flow.

Instrumentation - In addition to the standard factory test engine instrumentation, there were air temperature and pressure rakes at the compressor inlet and discharge to measure compressor efficiency, and also temperature and pressure probes at the rotor main cavity inlet and discharge to monitor the cooling air flow.

The compressor mechanical instrumentation shown in Figure 2 included the stator casing and rotor structure thermocouples, the clearanceometers and the touch probes. The touch probes were used to doublecheck the clearanceometers at the steady-state engine running conditions.

The clearanceometers used were electrical capacitance probes whose output voltage varies with the distance between the clearanceometer and the passing blade tips. A touch probe is a traverse probe with an open electrical circuit which closes when the probe touches the passing blade tip. When contact is made, the probe automatically backs off. The distance traversed by the probe to touch the blade tip is measured by a linear potentiometer.

Engine Tests

The tests were run in the General Electric Altitude Test Facility. They included steady-state power calibration tests, rapid accels and decels and a simulated typical flight cycle. The steady-state power calibration tests were made with three different engine inlet conditions, which were the core engine ambient, the simulated fan engine sea level static and cruise inlet conditions, and at a number of different engine speeds. At each speed point, at least three different sets of clearances were produced and their effects on engine performance were measured.

The test procedure was as follows. After the engine inlet condition and speed were stabilized, the rotor bore cooling air flow was set at the desired level, and three minutes later all instrumentation sensors were scanned and their outputs recorded. Instrumentation scanning and recording of data was repeated approximately every three minutes until the rotor disk temperatures became stable, which took fifteen to twenty minutes. At this point, the cooling air flow was changed and scanning of instrumentation sensors and data recording was repeated.

The simulated flight cycle and the rapid accels and decels, which included hot rotor rebursts, were made to evaluate potential improvements in clearance control. The tests were run with ambient engine inlet conditions and two different sets of clearances. The rapid accels were made from ground idle to take-off power setting which was then held constant until rotor disk temperatures became stable after which the engine was rapidly deceled to ground idle.

A hot rotor reburst is said to occur when an engine is rapidly deceled from a high to a low power setting and after a short time at the low power is reburst back to the high power setting. This type of power throttle maneuver may result in the most adverse tip clearances in the aft end of the compressor, particularly if the engine dwells at the low power setting for such a time period so as to produce the maximum temperature difference between the rotor and stator structures. In the hot rotor reburst tests, the metal temperatures were stabilized at take-off, then the engine was rapidly deceled to ground idle and a short time later, it was reburst back to take-off where the metal temperatures were again permitted to stabilize. Time at ground idle varied from approximately one minute to thirty minutes. In these tests, both the transient and the steady-state data were recorded.

Results and Discussion

Results discussed here are the steady-state differences in rotor temperature, compressor clearances, compressor efficiency and engine fuel flow produced by different quantities of the rotor bore cooling air flow. Typical results are shown for one particular speed point, the simulated sea level static take-off point. The compressor efficiency changes and the engine fuel flow changes are then shown as functions of normalized average compressor airfoil tip clearance changes. Analysis of the transient test data has not yet been completed, and, therefore, these data could not be included. Finally, the most significant cause of compressor clearance degradation in the CF6-50 field engines is briefly discussed and some data are presented to underscore the relevance of this compressor clearance evaluation program.

Rotor Temperatures - The axial temperature profiles in the rotor main cavity are shown in Figure 3 for different rates of cooling air flow. The data indicate a greater rate of change in the aft end than in the forward end of the rotor, which is primarily due to the geometrical differences of these two areas of the rotor structure and, to some small extent, due to the higher conductivity of Inco 718 as compared to titanium. The data also show, as would be expected, that the higher the cooling air flow the lower the air temperature of the rotor cavity and of the disk bores as shown in Figure 4. At stage 14, the maximum cooling air flow reduced the air and metal temperatures by at least 300° F, which is a very significant reduction and somewhat greater than the pre-test predictions indicated.

Radial temperature profiles in the stage 14 disk are shown in Figure 5. The cooling air was most effective at the disk bore. The rim of the disk was much less affected where the maximum temperature reduction was about one quarter of that at the bore. In other stages, this was even a smaller fraction. Similar temperature profiles were generated for all other power calibration points, and they were used to calculate the airfoil tip clearance changes which are discussed in the next paragraph. As will be noted, the pre-test predictions significantly underestimated the effectiveness of rotor bore cooling.

Airfoil Tip Clearance Changes - At the power calibration points, the stator casing temperatures remained constant, and only the rotor temperatures were affected by the cooling air flow. Therefore, to calculate the clearance changes, only the rotor temperature changes needed to be considered. Clearance changes calculated in this manner, for the simulated sea level static take-off power calibration point, are shown in Figure 6 for different cooling air flow rates. Similar calculations were made for all other power calibration points. These data were then used to calculate the normalized average clearance changes which were later correlated with the corresponding measured compressor efficiency and engine fuel flow changes. The correlations are discussed in a later paragraph where the normalized average clearance is also defined.

The measured and calculated clearances for stages 10, 12 and 13 are shown in Figures 7-9. There is an excellent agreement for stage 10. For the other two stages, there are small discrepancies between measured and calculated data. The causes of these discrepancies have not yet been determined.

Efficiency and Fuel Flow Changes - Compressor efficiency changes as a function of the cooling air flow are shown in Figure 10. The data were measured at the simulated sea level static take-off conditions. Indicated and corrected values are shown in the figure. The corrections were made to obtain the net effect of clearance changes by allowing for

1) leakage of cooling air into the compressor inlet and

2) heat removed from the gas path by the cooling air.

The magnitude of the latter correction was about ten times as large as that of the former. Colder cooling air, leaking into the compressor inlet, slightly reduced the actual air temperature downstream of the inlet temperature rakes and, therefore, made the actual efficiency reduction, caused by increased clearances, slightly larger than the indicated reduction calculated from the measured temperatures and pressures at compressor inlet and discharge. Heat removed from the gas path by the cooling air reduced the indicated compressor discharge temperature and, hence, made the indicated efficiency reduction, due to the increased clearances, somewhat smaller than the actual reduction.

Engine fuel flow changes as a function of the cooling air flow are shown in Figure 11. The corrections made to the fuel flow were in the opposite direction to that of the efficiency corrections, i.e., the fuel flow corrections resulted in a smaller actual fuel flow change than that indicated, because the measured fuel flow included the energy removed from the cycle by the cooling air which was vented overboard. If the clearance changes were produced mechanically, there would be no heat loss from the cycle, and therefore, the total fuel required would be less.

The compressor efficiency and fuel flow changes were corrected in this manner for all power calibration speed points and then correlated with the average normalized clearance changes which are discussed in the next paragraph.

Correlation of Efficiency and Fuel Flow Changes with Clearances - Compressor efficiency changes are shown as a function of the normalized average clearance changes in Figure 12 for four different speed points with three different engine inlet conditions. There is a good correlation of measured efficiency changes with the calculated normalized average clearance changes. The normalized average clearance change is defined as follows:

$\Sigma \Delta CL/L$, where:

ΔCL = clearance change in a given stage and

L = airfoil length in the same stage.

The line shown in the figure is the best line drawn through the data points.

The engine fuel flow changes versus the normalized average clearance changes are shown in Figure 13. Only the data obtained at the simulated sea level static take-off and cruise conditions are presented. The data for the other two speed points were inaccurate because of a fuel flow meter malfunction. The line shown in the figure is derived from the efficiency line in Figure 12 through the derivative of fuel flow as a function of efficiency for the test engine. Because the line correlates well with the fuel flow data, it, therefore, indicates consistency of the efficiency and fuel flow changes.

Compressor Clearance Degradation

Compressor stator casing out-of-roundness has been found to be the most significant cause of airfoil tip clearance degradation in revenue service engines. The effect of casing out-of-roundness on compressor blade and vane clearances is shown in Figures 14 and 15, respectively. To meet the minimum clearance at build-up, all blade tips have to be machined shorter by the amount equal to at least the inward distortion. Vanes, on the other hand, only need to be machined shorter in the area of the inward casing distortion.

The effect of out-of-roundness on clearances is magnified for two reasons. First, the permitted interchangeability of modules and, second, because of the field shop practices at engine build-up. At every shop visit, the distorted casing may be installed in a different compressor module, thus causing short blades and hence increasing the clearances in all of them.

The field shop practices involving out-of-round casings at engine build-up require that the individual compressor rotor and stator casing modules are machined to meet a target minimum clearance. However, verification of the actual minimum clearance is required, and this is accomplished by applying wax strips of known thicknesses to the stator casing and rotor spool lands and then installing the casing halves around the rotor. The rotor is then rotated through 360^{o} after which the stator casing halves, upper and lower, are removed and the wax strip thicknesses are measured. If the wax strips were rubbed, indicating below minimum clearance, then the airfoil tips are hand ground to correct this condition. How the magnifying effect on clearances is produced will be illustrated by a specific field engine incident. An engine that failed to meet the minimum performance standards was disassembled and inspected. Inspection of the compressor, which had been refurbished prior to the test cell run, indicated out-of-roundness in the stator casing which is shown in Figure 16. The rotor blade tips in the aft end of this compressor were rounded off by hand grinding at assembly, because of below minimum clearance due to the out-of-round stator casing. A rounded-off blade tip from this compressor is compared to a machine ground blade tip from another compressor in Figure 17. The casing out-of-roundness in the aft end was a maximum of 20 mils, but the blade tips were up to 40 mils shorter at the leading and trailing edges. This is a good example of how the effects of an out-of-round casing on the average clearances are magnified. Hand grinding is not acceptable for this purpose. A procedural change has been specified to require remachining rather than hand grinding in similar cases.

Out-of-roundness data from a survey of twenty-six stator casings are summarized in Figure 18, where three sets of values are shown, i.e., the average of all measured and the largest measured in modules B and C. Although the average values were only about 10 mils, the maximum values were as much as 30 mils. Out-of-roundness of the module B stator casing, in particular, had a very significant impact on performance, since the clearances in the aft end of this module had to be increased by at least 20 to 30 mils. To avoid this large performance penalty, field procedures have been specified for the repair of casing out-of-roundness.

Concluding Remarks

The data presented are preliminary and are still being analyzed, but they indicate that the test technique was effective. By means of rotor bore cooling, appreciable changes were produced in rotor temperatures, compressor airfoil tip clearances, compressor efficiency and core engine fuel flow. A good correlation was obtained of measured and calculated clearances. Compressor efficiency changes correlated well with the normalized average clearance changes, and, furthermore, they were consistent with the corresponding fuel flow changes. The clearance changes produced in this engine test were comparable to the maximum clearance degradation observed in the revenue service engines. Significant fuel savings can be achieved if clearance degradations in the revenue service engines are reduced or eliminated. The results of this test are being applied to the development of new General Electric commercial engines.

HIGH PRESSURE TURBINE ROUNDNESS/CLEARANCE EVALUATION

Program Scope

As an engine accumulates operating time in revenue service, its performance deteriorates as a function of time and operating cycles. A significant part of the CF6 engine performance deterioration is chargeable to the high pressure turbine. This deterioration is primarily due to increased blade tip-to-shroud clearances caused by rubbing of the blade tips on the shrouds. The objective of the HP turbine clearance and roundness diagnostics program was to provide test data to improve the understanding of the effect of blade tip clearance on performance as affected by transient engine operating conditions and of stator out-of-roundness.

Engine Tests

The tests were conducted in Test Cell 2 at the General Electric Company Plant in Evendale, Ohio. The test vehicle was a CF6-50C engine. The engine was mounted in an overhead frame as shown in Figure 19.

Blade tip clearance data were obtained from clearanceometer probes especially designed for this purpose. Eight of these clearanceometer probes were installed in the engine which had been modified to accept the probes as shown in Figures 20 and 21. The probes were located circumferentially around the engine over the stage 1 blade tips as identified in Figure 22. Clearance data was then recorded for the type of engine operations shown typically in Figures 23 and 24. These operations included numerous steady-state and transient operating conditions.

Test Results

Measured data from each of the eight clearanceometer probes were averaged to obtain the "round engine" clearance. This clearance, plotted against time, defines the round engine clearance response. The "round engine" data were then used for tuning axisymmetric analytical models of the modified test engine configuration. This knowledge was then utilized to upgrade the production configuration engine analytical model.

Representative plots of a throttle burst (steady-state idle to steady-state take-off) and throttle chop (steady-state take-off to steady-state idle) are presented in Figures 25 and 26.

Evaluating the results of each of the individual clearanceometer probes relative to the averaged data for any given time yields a measured "out-of-roundness." These data were then used in conjunction with calculated mechanical loads and calculated thermal distortions to identify deficiencies, and they formed the basis for correction of the calculated results. Out-of-roundness results are shown in Figures 27 and 28 for throttle bursts and chops respectively.

Discussion of Results

The "round engine" clearance transient response results matched pre-test calculated predictions closely as did clearance at steady-state operating points. This clearance match was also confirmed by thermocouple data from the shroud support, and it verified that the anlytical modeling previously used was representative of the engine structure. Some relatively minor model parameter adjustments were necessary to force calculated results to more perfectly match measured clearance responses. The test verified the calculated importance of hot or warm rotor throttle rebursts on minimum blade tip clearance experienced in engine operation.

Calculations predicted that steady-state engine operating clearances are set at engine transient operating conditions. The worst case or minimum clearance condition, occurs during a hot rotor reburst which has idle dwell times less than 3 to 4 minutes.

The turbine shroud support member is considerably less massive than the turbine disk and, consequently, cools more quickly than the disk. The rapid reacceleration of the engine adds rotational stress growth and blade thermal growth to the still existent disk thermal growth. The net result is a hot blade tip radius greater than that of the supporting structure, which results in rubs.

A significant part of engine deterioration may be caused by "warm rotor rebursts" (idle times over 4 minutes) for which little data was available. Testing included several runs to provide data relative to this type engine operation. Rebursts with idle dwell times of 8, 6, 4, 2, 1 and 0.5 minutes were completed to quantitatively evaluate these significant round engine and out-of-roundness responses for which good analytical predictions were not available.

Out-of-roundness was evaluated for all the steady-state and transient operations tested. Pre-test predictions of out-of-roundness at steady-state conditions were compared to measured out-of-roundness. While the results compared well in magnitude, the shapes differed sufficiently to indicate that out-of-roundness driving phenomena existed which were not accounted for analytically.

However, test results did clearly indicate that the phenomena not accounted for in the analysis were thermal and not mechanical load induced. Testing and analysis accounted for mechanical distortions caused by engine thrust, redundant torque, and mount horizontal and vertical loads as well as manufacturing tolerances. These distortions agreed very well with analytical predictions. Test data also included temperature measurements for portions of the engine structure which were analytically determined to affect turbine stator roundness. They included combustor exit temperature profile, turbine mid-frame temperature distributions, shroud support temperature distributions and low pressure turbine case temperature distributions. These temperature measurements lead to improvements in out-of-roundness data correlation.

Comparison of test results, field-observed turbine deterioration rates, and rub locations agree well and verify that most turbine blade tip clearance deterioration is the result of combined stator out-of-roundness and warm rotor rebursts.

Concluding Remarks

As a result of this program accurate measurements of HP turbine clearances and out-of-roundness were obtained for steady-state operations as well as throttle bursts, chops and rebursts from various dwell times at ground idle. The measured average clearances agree well with the analytical predictions.

The learning gained from this testing and from subsequent analytical refinements is being applied to identify potential improvements in turbine efficiency for the CF6-50 and several other engine models. This is especially true in the development of enhanced ability to optimize HP turbine rotor-to-stator transient response rate and stator out-of-roundness calculations.

Instrumented Core Engine In Altitude Test Facility

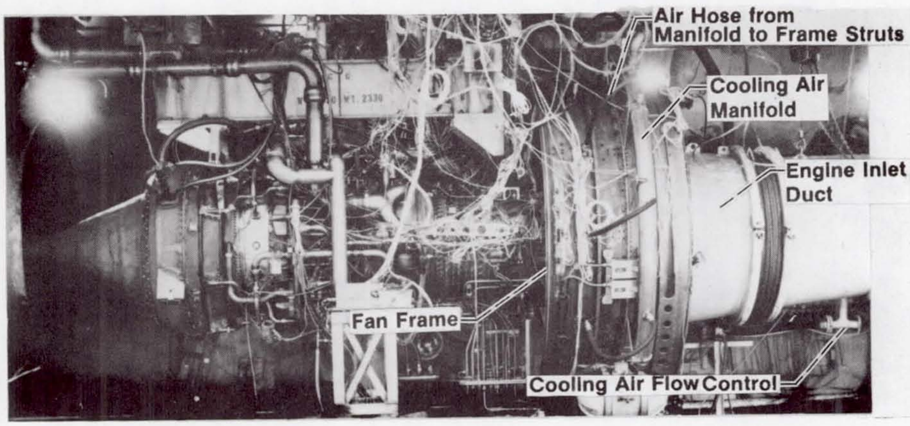

FIGURE 1

Compressor Instrumentation/Flow Schematic

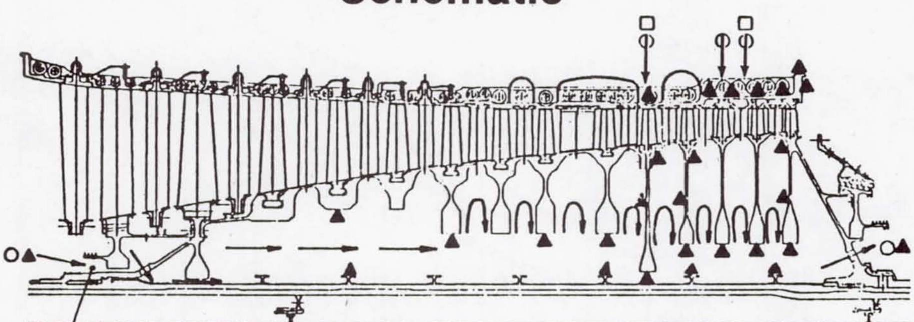

FIGURE 2

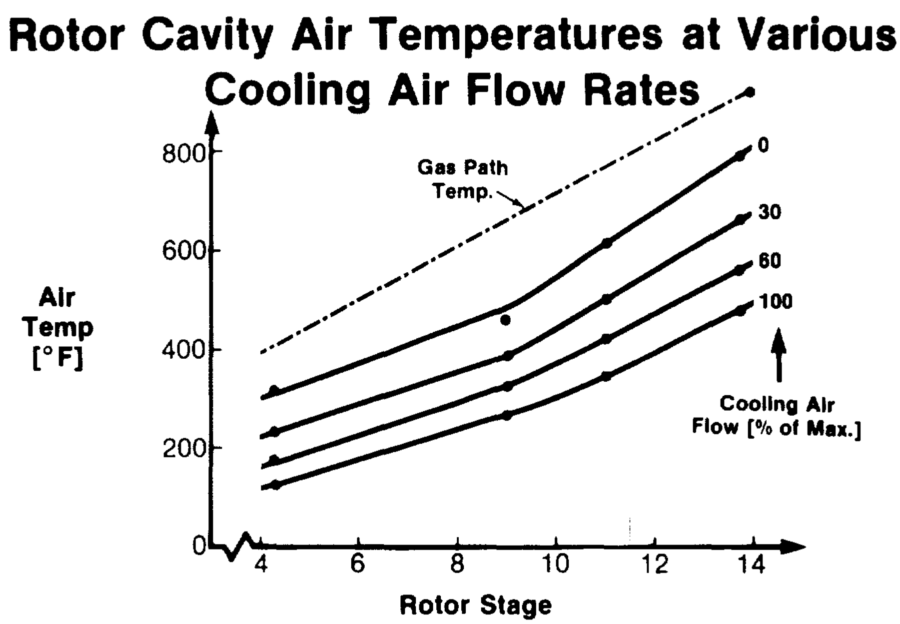

FIGURE 3

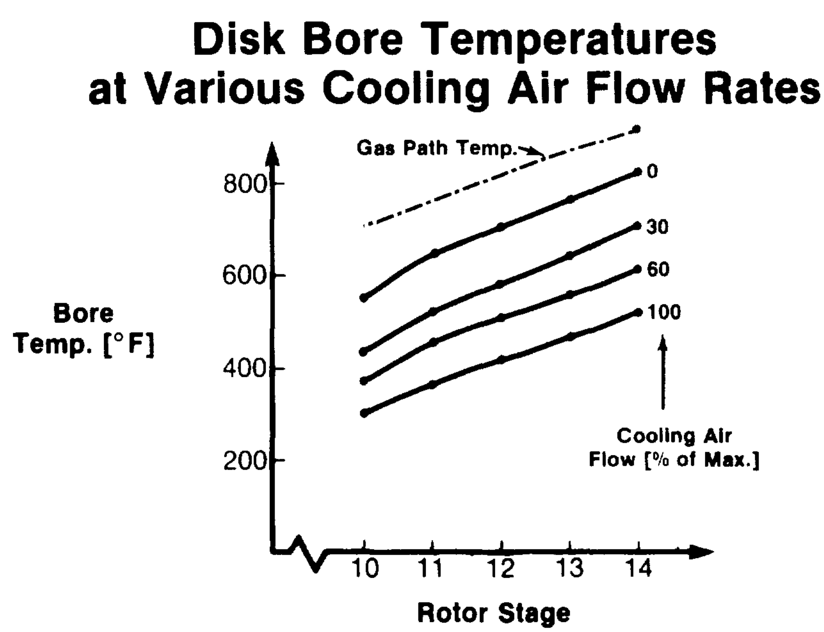

FIGURE 4

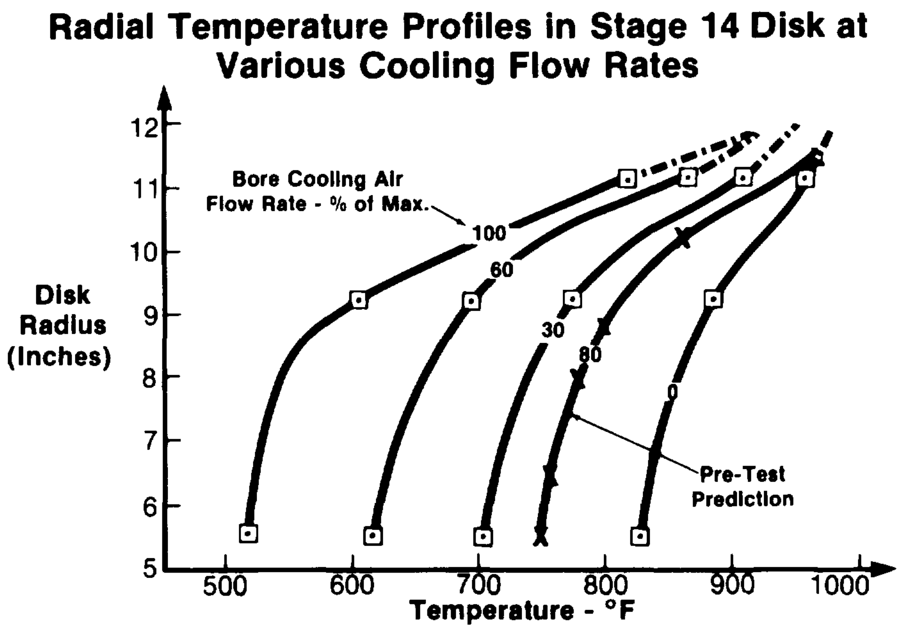

FIGURE 5

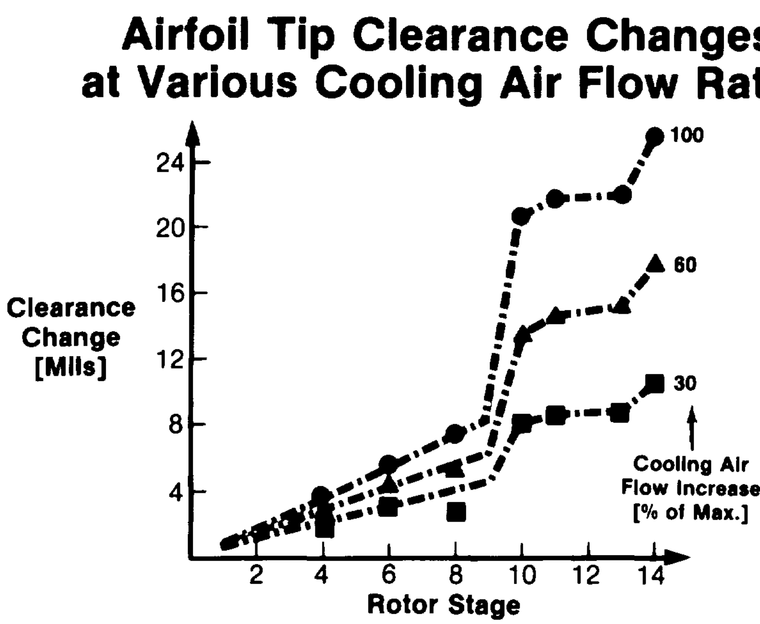

FIGURE 6

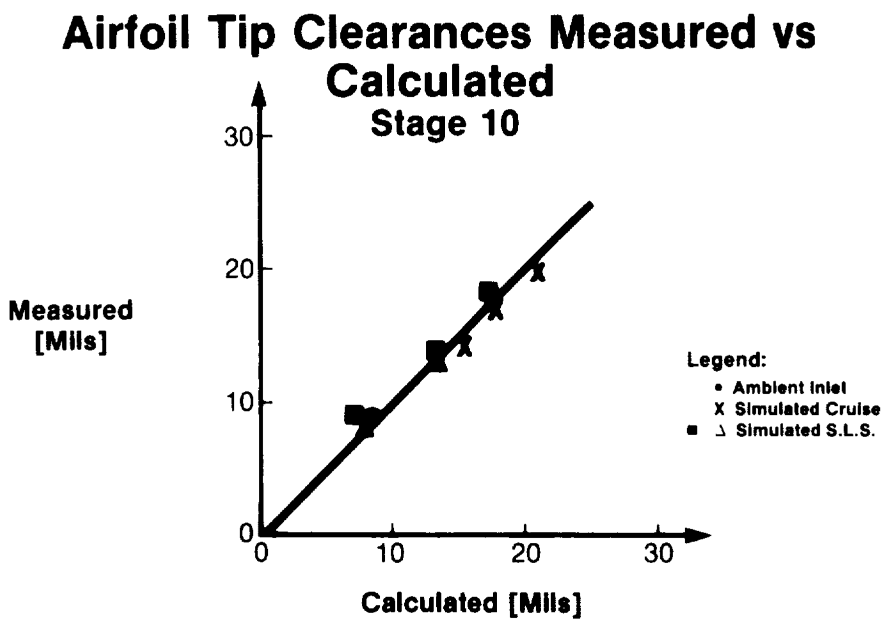

FIGURE 7

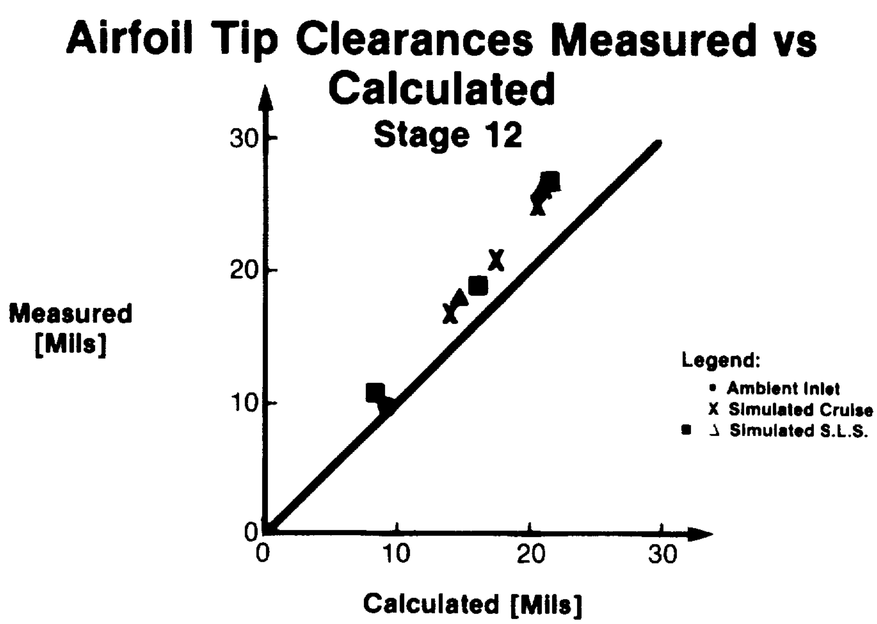

FIGURE 8

Airfoil Tip Clearances Measured vs Calculated

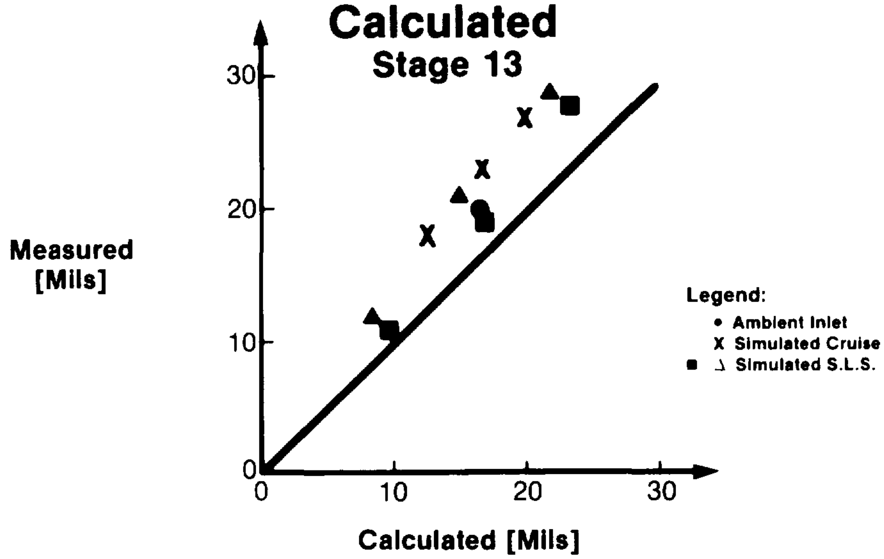

FIGURE 9

HPC Efficiency vs Cooling Air Flow

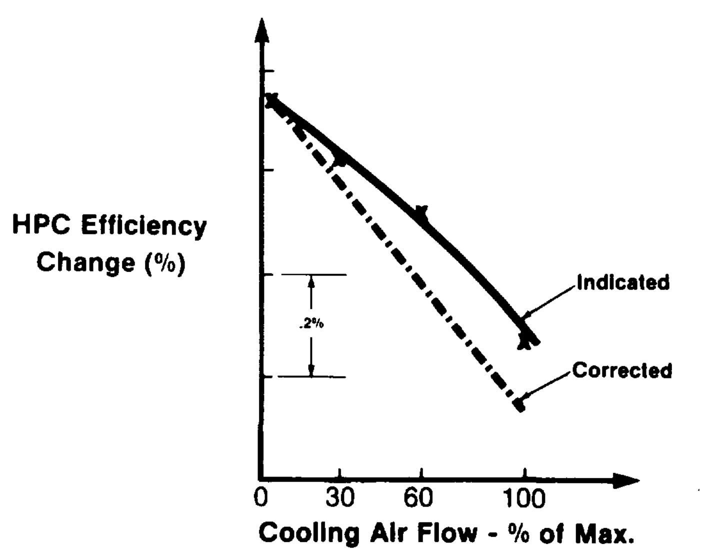

FIGURE 10

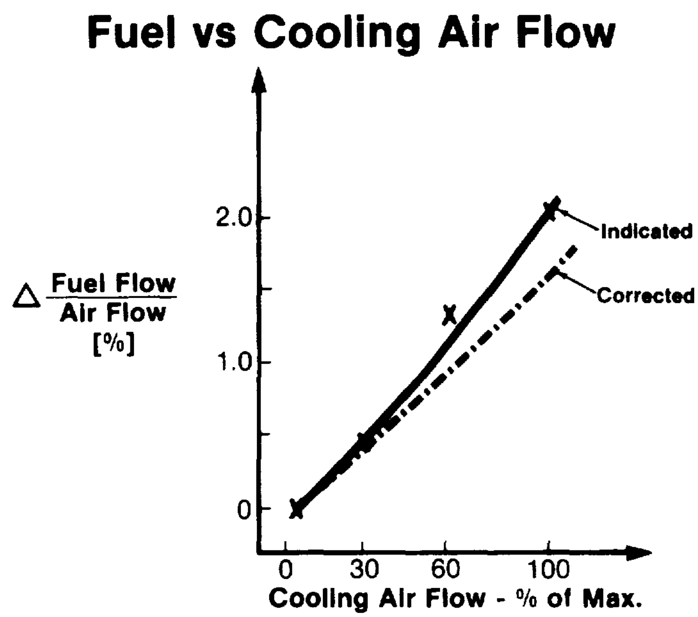

FIGURE 11

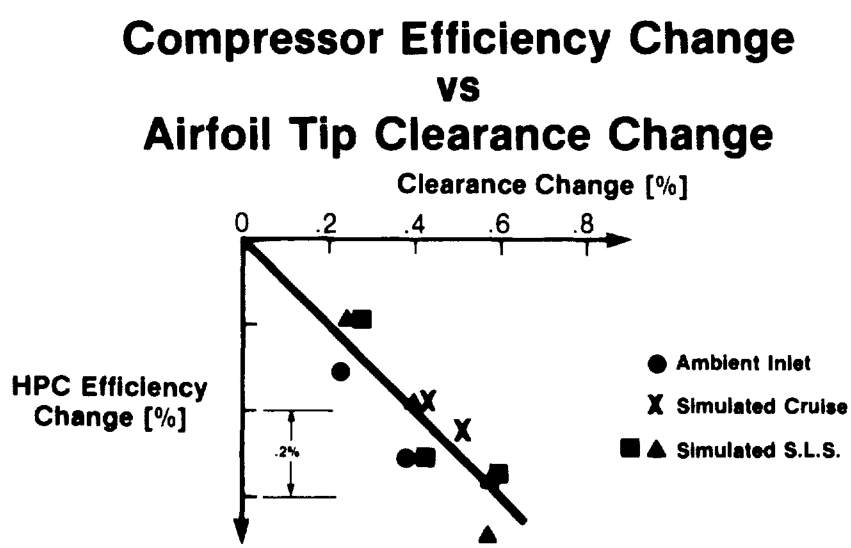

FIGURE 12

Fuel Flow Change vs Airfoil Tip Clearance Change

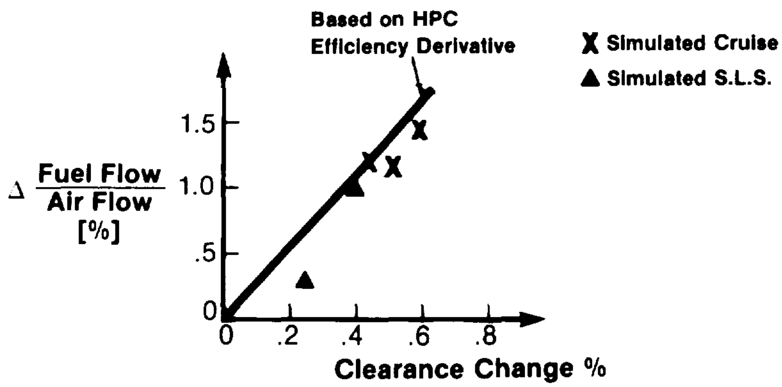

FIGURE 13

Effect of Casing Distortion

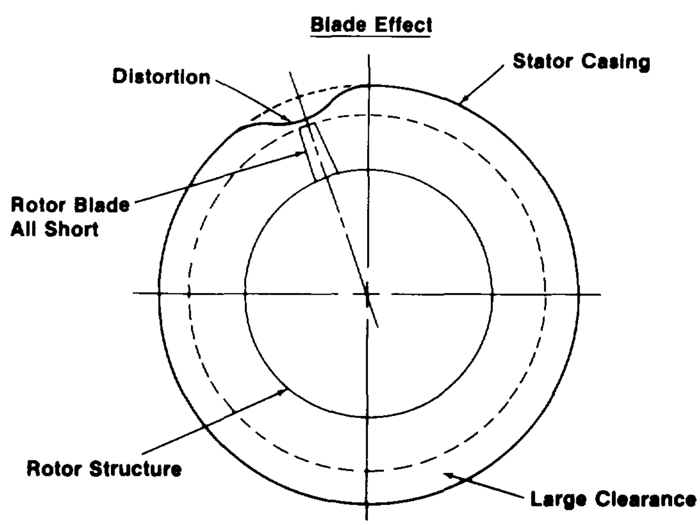

FIGURE 14

Effect of Casing Distortion

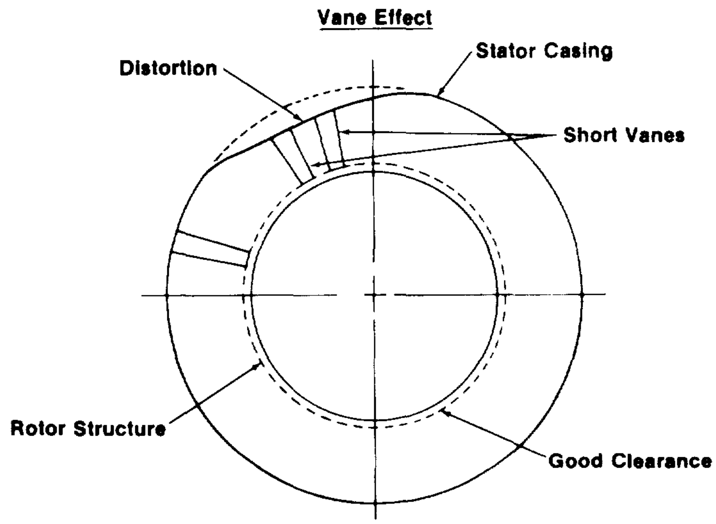

FIGURE 15

Casing Out of Roundness vs Stage

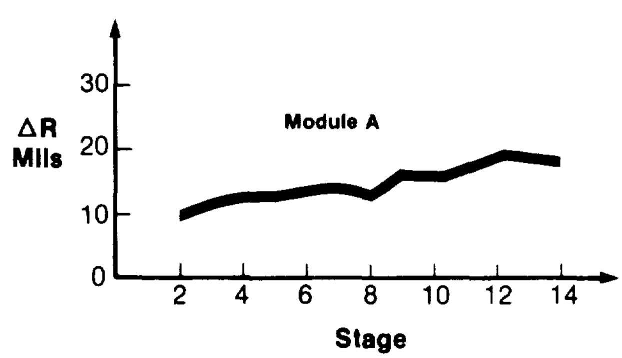

FIGURE 16

Hand Grinding of Blade Tips at Assy

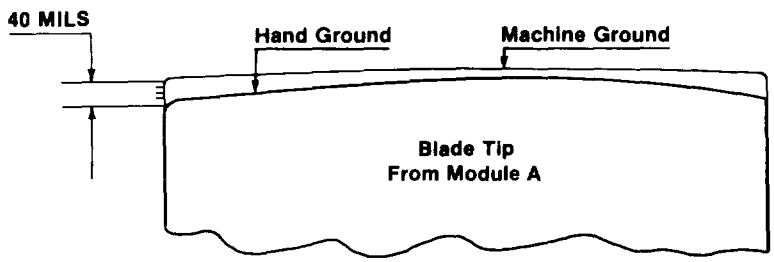

FIGURE 17

Casing Out of Roundness vs Stage

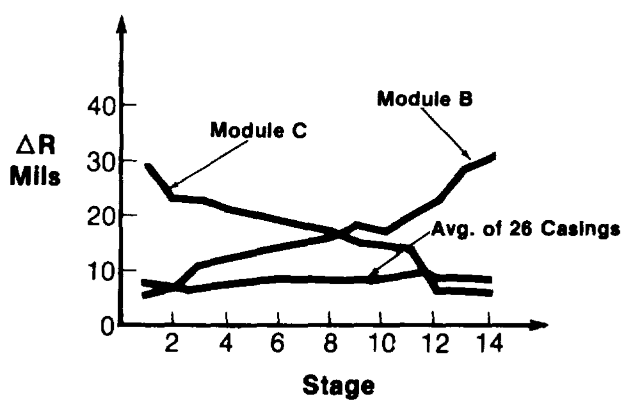

FIGURE 18

Instrumented CF6-50 Engine In Test Cell

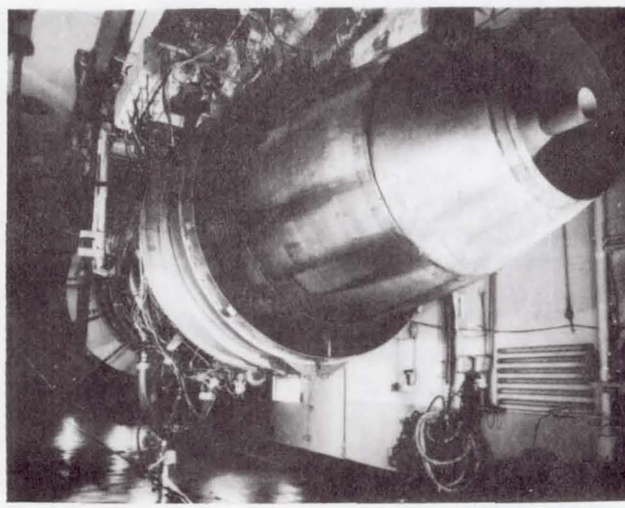

FIGURE 19

Current CF6-50 HPT Cross Section

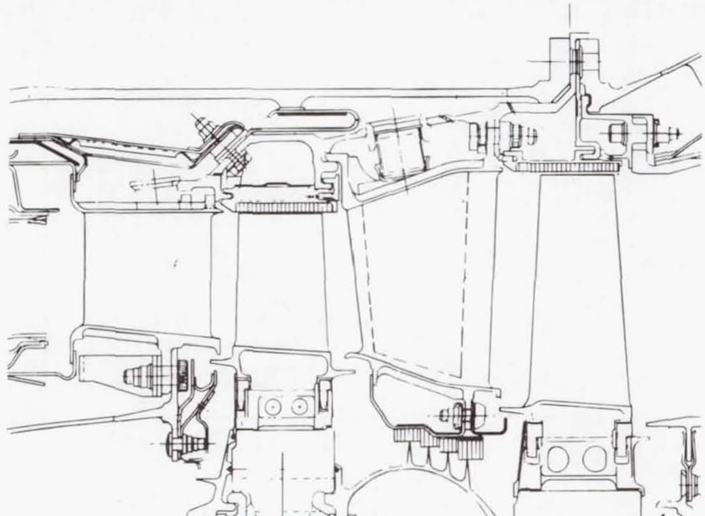

FIGURE 20

Turbine Modification to Receive Clearanceometer Probes

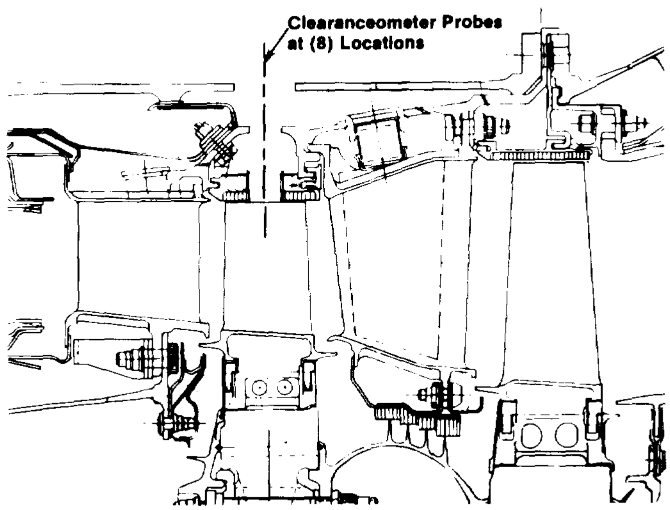

FIGURE 21

Probe Angular Position (ALF)

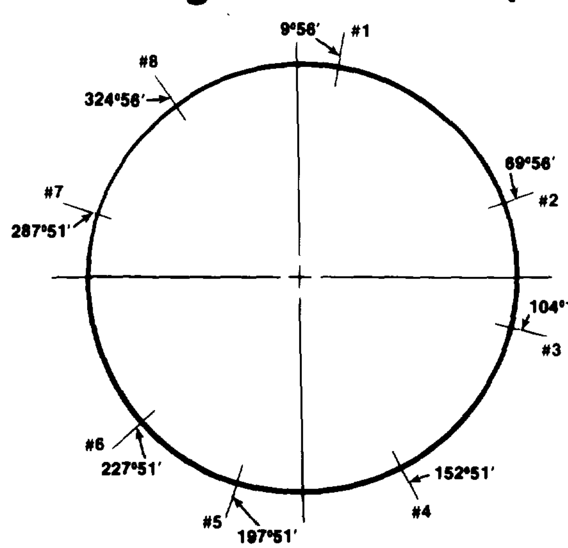

FIGURE 22

Test Sequence
Throttle Bursts and Chops

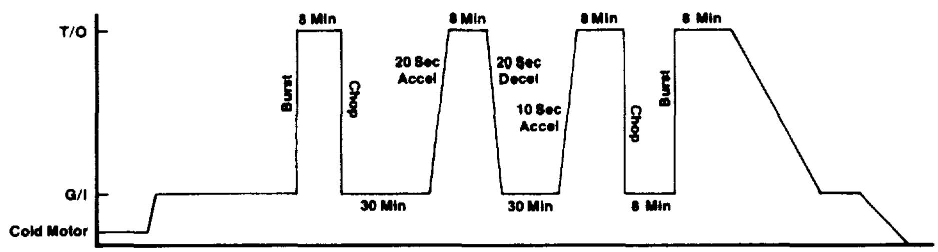

FIGURE 23

Test Sequence
Power Calibration

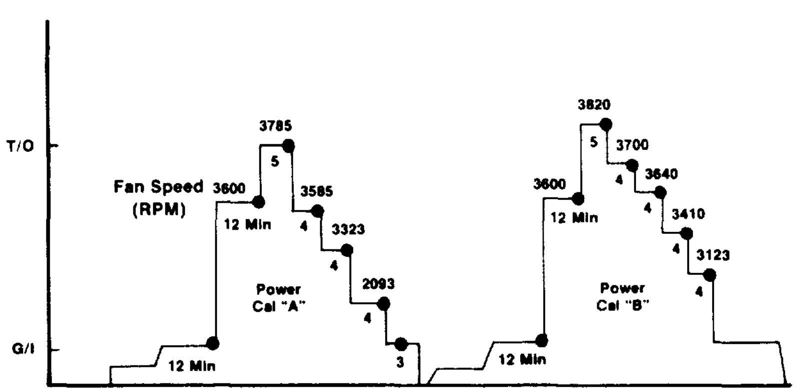

FIGURE 24

Blade Tip Clearance Transient Response — Throttle Burst From Idle To Take-off

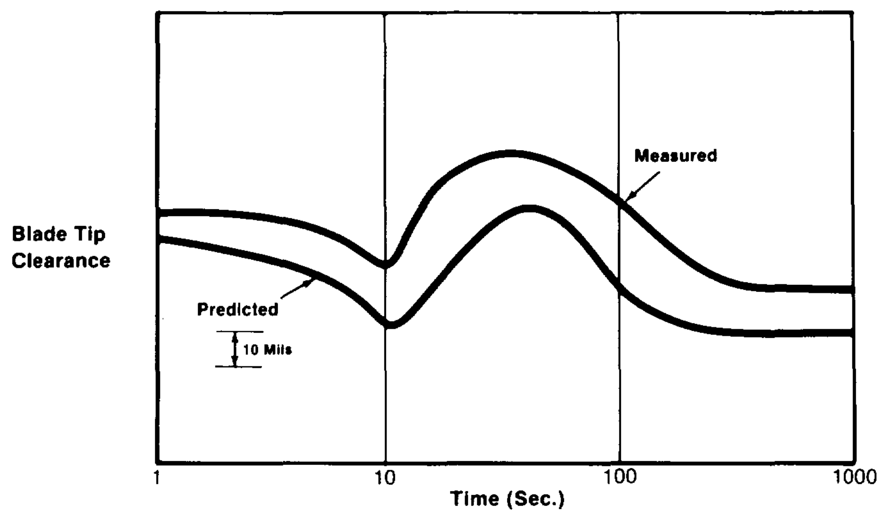

FIGURE 25

Blade Tip Clearance Transient Response — Throttle Chop From Take-off To Idle

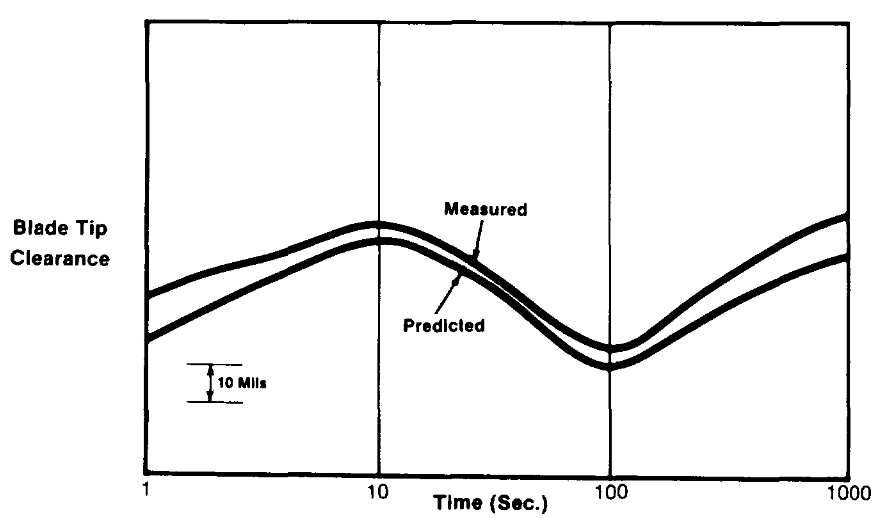

FIGURE 26

Stator Out-Of-Roundness — Throttle Burst

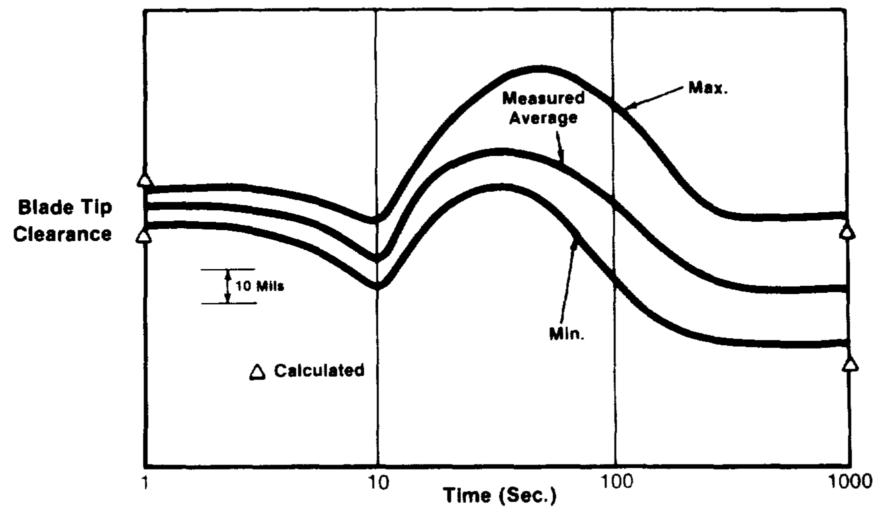

FIGURE 27

Stator Out-Of-Roundness — Throttle Chop

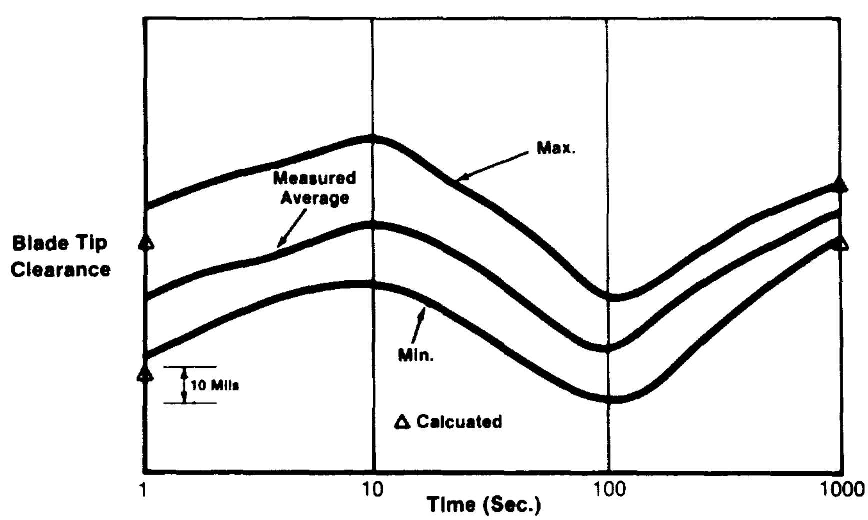

FIGURE 28